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This report discusses the investigation of the frequency stability characteristic of single-frequency Nd:YAG lasers. Technical Results reported include; ~~(1)~~ The locking of a single-frequency Nd:YAG laser to the bandpass of a high finesse Fabry-Perot interferometer; ~~(2)~~ the unification of etalon thermal tuning of the laser for course frequency control; ~~(3)~~ the construction of a second single-frequency laser; and ~~(4)~~ the heterodyning of the two single-frequency YAG lasers at a variable frequency offset.

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SUMMARY

The effort under this contract involves an investigation of the frequency stability characteristics of single-frequency neodymium:YAG lasers and picosecond pulse applications. Work during this reporting period has been concerned only with the first of these areas. The YAG lasers employed in this investigation incorporate proprietary techniques to achieve single mode, single-frequency output. The major technical accomplishments have been: (1) the locking of a single-frequency Nd:YAG laser to the bandpass of a high finesse Fabry-Perot interferometer; (2) the unification of etalon thermal tuning of the laser for course frequency control; (3) the construction of a second single-frequency laser; and (4) the heterodyning of the two single-frequency YAG lasers at a variable frequency offset. The next step in the investigation will be the locking of the two lasers together with a fixed frequency or zero frequency offset.

The development of stable, single-frequency YAG lasers and the locking of these lasers together constitutes a highly significant technical accomplishment and important for many of the applications forecast for Nd:YAG lasers.

Frequency Instabilities in the Single-Frequency Nd:YAG Laser.

Single-Frequency Nd:YAG

Frequency variation of the single-frequency Nd:YAG laser output is of two types. The first is a "quantized" frequency change in which the laser output jumps from one cavity mode to the adjacent mode. The particular cavity mode which oscillates is determined by the band pass of an intracavity etalon. As the temperature or angle of the etalon changes, the band pass peak shifts in frequency and it is the cavity mode nearest this peak which oscillates.

The second type of frequency variation arises from changes in the cavity mirror spacing due to thermal effects, and to variation in the optical path length due to changes in index of refraction of cavity material. Such index changes result from variation of either the pump power or of the rod cooling rate or from changes in the ambient air temperature of pressure. Both types of frequency instability will be considered in more detail below.

The "quantized" frequency change in the laser output is shown in Fig. 1 which is a time exposure of the Fabry-Perot display. The laser oscillates in one cavity mode and then jumps to the adjacent mode which is separated by approximately 500 MHz. The deleterious effect of this change is that during the transition the laser will oscillate in both modes simultaneously and the output is no longer at a single frequency. The particular cavity mode which oscillates is determined by the band pass peak of an intracavity etalon. As the temperature or the angle of the etalon changes, the band pass peak shifts in frequency and it is the cavity mode nearest this peak which oscillates. For now consider only the temperature dependence. The effect can be understood by referring to Fig. 2, where the etalon transmission characteristic has been intentionally exaggerated. If the temperature of the etalon changes from T_1 to T_2 , the position of the transmission peak will shift and the laser will oscillate at a new cavity mode which is displaced in optical frequency from the original frequency. Assume that the cavity mode spacing remains constant with a change in the etalon temperature. The shift in the laser operating frequency due to the etalon effect is quantized in the sense that the transmission peak can take an excursion equal to one-half the cavity mode spacing before a frequency change occurs. Another point to be made is that the band pass peaks of the etalon are separated by $c/2n\ell$, where ℓ is the length of the etalon and n is its index of refraction. The laser will oscillate at the cavity mode which is nearest to the band pass peak of the etalon transmission which, in turn, is nearest to the maximum of the laser gain profile curve.

The transmission peak of the etalon formed by a intracavity flat-ended component is at a frequency given by

$$f = q \frac{c}{2n\ell} \qquad (1)$$

where: q = a large integer
n = index of refraction
ℓ = length

We assume that both n and ℓ depend on temperature, and that the dependence of n on f can be neglected.

The laser will oscillate at the cavity mode which is nearest in frequency to the etalon transmission peak. Of interest is the temperature tuning characteristic of the transmission peak which is given by:

$$\frac{df}{dT} = -f \left\{ \frac{1}{n} \frac{dn}{dT} + \frac{1}{\ell} \frac{d\ell}{cT} \right\} \qquad (2)$$

The coefficient of linear thermal expansion is given by:

$$\alpha = \frac{1}{\ell} \frac{d\ell}{dT} \qquad (3)$$

Thus,

$$\frac{df}{dT} = -f \left\{ \frac{1}{n} \frac{dn}{dT} + \alpha \right\} = - \eta f \qquad (4)$$

The optical frequency of the transmission peak depends on two terms, one representing the change in index, the other the change in length of the component and the combined effect is given by η which is a material constant.

The intracavity etalon in the laser is made of fused quartz with $\eta = .5 \times 10^{-5}/^{\circ}C$ and therefore $df/dt = 1.4$ GHz/°C. If the maximum allowable frequency excursion of the transmission peak is $\pm$ 250 MHz, before the laser begins to oscillate at the adjacent cavity mode, the etalon temperature needs to be held to within $\pm$ .18°C. The required temperature stability is achieved by placing the etalon in a commercially available crystal oven.

It is known that the laser rod can also appear as a mode selecting etalon even though the ends of the rod are anti-reflection coated (<.2 percent reflectance). This is apparent from a Fabry-Perot display of the laser output where the optical modes are found to be near multiples of c/2nL where nL is the optical length of the rod. If the band pass peak of the rod etalon determines the cavity mode which oscillates, and if the maximum frequency excursion of this peak is $\pm$ 250 MHz, then the temperature of the laser rod ($\eta = 1.1 \times 10^{-5}/^\circ C$) needs to be held within $\pm$ .08°C. Holding the rod temperature within this range is very difficult because of fluctuation in the rod cooling water temperature, varying cooling rates between the rod and the water due to water turbulence, and varying thermal input to the rod because of pump lamp variations. For this reason, it is necessary either completely eliminate the rod etalon or to make it a very low finesse etalon compared to another intracavity etalon which can be carefully controlled in temperature.

A change in the laser operating frequency can also result from an angular change of the intracavity etalon with respect to the beam axis of the laser (Ref. 1). Consider an etalon of length ℓ, refractive index n and inclined to the incident beam at a small angel θ. The internal angle between the light path and the normal to the etalon surface is θ' θ/n. The transmission maximum of the etalon is given by:

$$2n\ell \cos(\theta') = M\lambda \qquad \text{M is an integer} \qquad ((5)$$

For small θ',

$$2n\ell\,(1 - \theta^2/2n^2) = M\,(\lambda_o - \Delta\lambda) \qquad (6)$$

where λ_o is the resonant wavelength for $\theta = 0$; i.e., $2n\ell = M\lambda_o$, and $\Delta\lambda$ is the shift in the transmission peak due to the tilt. It follows that

$$\Delta\lambda = \frac{-\lambda\theta^2}{2n^2} \qquad (7)$$

or

$$\Delta f = \frac{f\,\theta^2}{2n^2} \qquad (8)$$

The angle tuning curve depends only on the index of refraction and not on its length. The angular tuning curve is also quantized in the sense that the transmission peaks must be shifted by more than one-half the cavity mode spacing

before a frequency change will occur. As an example, suppose that the transmission peak can shift ± 250 MHz before the laser jumps to the adjacent cavity mode. The fused quartz etalon (n=1.5) needs to be held rigidly enough so that its angle with respect to the beam axis does not change by more than ± 2 millirad. In tilting the etalon, the optical path length of the cavity changes slightly and this gives rise to a change in the laser operating frequency which is usually negligible. It should be pointed out that even if the intracavity optical component is held perfectly rigid, it is the relative angle between the laser beam axis and the normal to the etalon surface which is important so that any beam wander in angle caused by index changes in the laser rod, for example, could cause an angular tuning effect.

The role of intracavity etalons in determining the frequency stability of a single-frequency laser has been considered. The main effect of etalons is to cause "quantized" frequency changes in which the laser output jumps from one cavity to the adjacent mode due to a shift in the etalon transmission peak. The importance of holding the etalon temperature and angle within narrow limits is apparent. The other aspect of frequency stability in the Nd:YAG laser is that of changes in the cavity frequency due to variation of the cavity length caused by index of refraction perturbations of the material in the laser cavity or from changes in the cavity mirror spacing due to temperature changes in the support structure. This type of frequency variation is shown in Fig. 3. A small length change $\Delta\ell$ together with a refractive index change in Δn occuring in a fraction f of the total length of the cavity results in a shift in the oscillation frequency given by:

$$-\frac{\Delta f}{f_2} = \left(\frac{\Delta\ell}{\ell} + f\Delta n\right) \qquad (9)$$

The change in frequency with changes in the cavity length ℓ has been separated into two parts: $\Delta\ell/\ell$ represents the change in length of the cavity due to changes in the physical distance between the cavity mirrors, and a part $f\Delta n$ which represents a change in the optical length of the cavity due to index of refraction changes in the cavity medium. The factors which contribute to the $\Delta\ell/\ell$ term are temperature changes in the cavity produced either by variations in the ambient or by variations in the input power to the laser which changes the thermal load on the surrounding cavity structure. For a change in temperature ΔT, $\Delta\ell/\ell$ is simply αT where α is the coefficient of thermal expansion of the spacer material separating the mirrors which make up the optical cavity. The changes in frequency of oscillation caused by $\Delta\ell/\ell$ are relatively slow due to the thermal mass of the spacer material.

The second term in Eq. (9) is due to changes in the optical path length of the cavity due to variation of the index of refraction in the cavity medium. Changes in ambient temperature, pressure, and humidity change n, and therefore, the optical length of the cavity. Another important index change is due to the Nd:YAG laser material which arise from variations of the input power to the laser rod, or changes in the rate of cooling of the rod. These effects and their magnitude are summarized in Table I.

TABLE I

Source of Frequency Change	$\frac{\Delta f}{f}$	Magnitude of Constant
Thermal Expansion of Cavity	$\alpha \Delta T$	$\alpha = 1 \times 10^{-7}/°C$
Atmospheric Temperature	$f_a \beta_T \Delta T$	$\beta_T = 9.3 \times 10^{-7}/°C$
Atmsopheric Pressure	$f_a \beta_p \Delta P$	$\beta_p = 3.7 \times 10^{-7}/\text{Torr}$
Laser Rod Index Change	$f \frac{dn}{rdt} \Delta T$	$\frac{dn}{dt} = 7.3 \times 10^{-6}/°C$

To put this into better perspective, again consider Eq. (9). Substituting for $\Delta \ell/\ell$ and the terms which contribute to Δn (from Table I).

$$\frac{-\Delta f}{f} = (\alpha + f_a \beta_T)\, \Delta T_c + f_a\, \beta_p\, \Delta P + f_n\, \frac{dn}{dT}\, \Delta T_R \qquad (10)$$

where ΔT_c is the change of the cavity structure and ambient air temperature, ΔT_R is the change in the laser rod temperature and ΔP is the change in ambient air pressure. For a cavity structure made from invar ($\alpha = 10^{-7}°C$) and for a laser rod which occupies .1 the total cavity length,

$$\frac{-\Delta f}{f} = (10^{-7} + 8.4 \times 10^{-7})\;\; \Delta T_c + 3.3 \times 10^{-7}\, \Delta P + 7.3 \times 10^{-7}\, \Delta T_R \qquad (11)$$

At constant pressure, the resultant cavity frequency shift due to ΔT_c is comparable in magnitude to the shift due to ΔT_R. The relative importance of the terms in Eq. (11) can be put in better perspective by realizing that changes in ΔT_c and ΔP occur relatively slowly over a period of tens of minutes and hours and they result in a long term "drift" of the cavity optical frequency. On the other hand, the temperature of the laser rod is the result of a delicate balance between the incident pump power and the cooling rate and this balance can easily be upset by a flicker in the lamp or bubbles in the cooling water. The laser rod temperature can change in a fraction of a second and it is the resultant cavity frequency changes in this time period which can be termed a frequency instability. Progress has been made toward reducing the temperature fluctuation in the laser rod. A comparison of Krypton arc lamps showed the ILC L661 lamp to have excellent amplitude stability with no tendency for arc wander and this is the lamp being used in the single-frequency laser. Even better lamp stability could be expected using tungsten filament lamps but this would be at the expense of the laser output power. Uneven cooling of the laser rod has been reduced by cladding the rod with a thin walled, transparent, fused quartz sleeve (Ref. 2) which extends the entire length of the rod. The sleeve has a thermal damping effect which integrates out any short term temperature fluctuations in the laser rod.

Frequency Stabilization of the Nd:YAG Laser

In order to relax the minimum temperature variation which can be tolerated on the cavity structure, a feedback loop is incorporated to further frequency stabilize the output of the single-frequency Nd:YAG laser. The requirement on the cavity structure and rod temperature are that they occur relatively slowly so that a feedback loop of a reasonable bandwidth can follow these changes. Feedback stabilized lasers incorporate basically the same elements as are utilized in stabilizing oscillators operating at lower frequencies (Ref. 3). Common to such systems is a null type frequency discriminator which converts deviation in the oscillator frequency from a reference frequency into a modulated ac error signal. The amplitude and phase of the error signal depend on the magntidue and sign of the frequency deviation from the reference. After phase sensitive detection of the error signal, the resultant dc signal is used to drive the oscillator frequency towards the discriminator null frequency. The short term response of such a system depends on the feedback loop bandwidth and the phase sensitive detector sensitivity. The long term stability of the system is no better than the stability of the reference.

Central to a system of this type is the frequency discriminator and since only relative frequency stabilization is of interest the problem is greatly simplified. Such discriminators have been devised which are based on the interference between two differentially delayed beams in a Michelson interferometer type of arrangement (Ref. 4). The delay may be introduced by differences in geometrical path length or by differences in refractive index. However, Michelson interferometer discriminators are not very attractive when compared to high Q

resonant cavity discriminators. Frequency stabilizers based on the use of high Q cavities have been used extensively in microwave systems since their development by Pound in 1946 (Ref. 3). Analogous system have been used at optical frequencies; however, due to difficulties in preserving the relative phase in the bridge arms, proposals for using optical cavities as discriminators have generally been based on their power tranmission or reflection properties rather than on their phase characteristics. (Ref. 5).

Optical cavities suitable for use in a frequency stabilization loop for the Nd:YAG laser are available commercially as scanning Fabry-Perot interferometers (SFP). These instruments, available from Tropel and Coherent Optics and others, are normally used as optical spectrum analyzers (Ref. 6) for the analysis of the laser optical modes, and without modifications, they are useful as the discriminator in the closed-loop stabilization scheme. The principle of operation is illustrated in Fig. 4. The center band-pass frequency of the SFP cavity is modulated at an audio rate, and the effect of this on the transmitted laser power is monitored with a photodetector. When the laser output drifts to one side of the reference cavity response, the output will be amplitude modulated at the cavity modulation frequency. On the other side of the reference cavity resonance, a signal of the opposite phase will result. A phase sensitive detector tuned to this audio frequency may be used to derive from the laser output a dc signal whose amplitude is proportional to the deviation from the center of the deviation. The resultant signal, after amplification, may be used to control the frequency of the laser cavity by a PZT driver mirror so that the output is stabilized on the center of the reference cavity response.

The output of the single-frequency Nd:YAG laser was stabilized using a commerically available (Lansing Model 80.210) feedback loop shown in Fig. 5. The reference cavity was a Coherent Optics Model 470 Fabry-Perot interferometer of 8 GHz free spectral and a finesse of approximately 125. The resultant half width of the cavity resonance is approximately 65 MHz. The frequency discriminant was obtained by dithering the reference cavity center frequency at a 520 Hz rate. Typically a .05 to .1 volt (RMS) dither voltage resulted insufficient modulation of the optical signal for lock-in. The dither voltage could just as well be applied to the PZT mirror on the laser cavity. The dc bias on the SFP is used to initially center the pass-band at the laser operating frequency. A bias change of 40 volts resulted in a scan of one free spectral range, or 8 GHz. The dc signal output of the phase demodulation was amplified and applied to PZT driven mirror on the single frequency laser. A second SFP of 1.5 GHz free spectral range and a finesse of approximately 150 was used to monitor the laser output as is shown in Fig. 6.

A comparison of the free running and the stabilized laser output is shown in Fig. 7. Without stabilization, the laser output frequency ranges over approximately ± 60 MHz in a 10 second time period. This frequency shift is due primarily to small changes in the pump power and in the rod cooling rate and with stabilization, the frequency excursions are reduced to ± 15 MHz. The range of frequency excursion over a number of minutes observation period does not change significantly from these values. The laser has remained stabilized for a period up to ½ hour.

Much better stabilization could be expected by using a faster responding feedback loop. This evidence in Fig. 8 where the envelope of the detected 520 Hz modulation signal is shown for a free running laser. The amplitude of the envelope changes as the unstabilized laser output sweeps through the pass-band of the reference cavity. As can be seen, there are frequency components to 10 Hz and above while the feedback loop response is limited to approximately 1 Hz. Of course, as the loop bandwidth is increased, noise and loop stability becomes a problem. The ultimate limit to the loop response is set by the mechanical resonances of the PZT mirror combination.

Single-Frequency Nd:YAG Laser Heterodyne

Heterodyne of the Nd:YAG laser presents special problems in the sense that the gain profile is very broad, spanning a frequency range of approximately 150 GHz. With no etalon in the cavity the laser will oscillate at the cavity mode nearest to theppeak of the gain profile. In practice, however, there usually are an intracavity etalons and the laser will oscillate at the cavity mode which is nearest to the peak of the etalon transmission curve which, in turn, in nearest to the peak of the gain profile curve. Two Nd:YAG lasers, although identically constructed and using rods made from the same boule of raw material could oscillate a number of GHz apart. The maximum the laser frequency can be shifted by PZT movement of a mirror is the cavity mode spacing which for this laser is 500 MHz. There are situations, such as optical heterodyne of two laser sources or laser oscillator-amplifier configurations where it is necessary to shift the laser frequency by an amount greater than that available from mirror movement alone. The temperature or angle variation of an intracavity etalon as discussed previously, can be used to increase the tuning range of the single-frequency Nd:YAG laser. By placing the etalon in a temperature controlled oven, the maximum tuning range is equal to the $c/2n\ell$ frequency of the etalon. For a 1 cm length of used quartz this frequency range is 10.3 GHz which is covered in a temperature range of 7.4° C. If a 1 cm length of calcite were used instead, the $c/2n\ell$ frequency would be 10.1 GHz which would be covered in a temperature change of 24° C. By using a shorter etalon, i.e., one with a larger free spectral range, correspondingly larger tuning ranges could be achieved. The etalon can be used for course frequency adjustment of the laser to within one cavity mode spacing

of the desired frequency. PZT movement of a cavity mirror can then be used for the fine frequency adjust.

The etalon thermal tuning technique for control of the laser operating frequency to within one cavity mode spacing (approximately 500 MHz) was verified by placing the intracavity etalon in a variable temperature oven. A unifrom increase or decrease of the oven temperature resulted in a monotonic shift of the laser frequency from one cavity mode to the adjacent mode as is shown in Fig. 9. The laser was swept over a 2 GHz frequency range, which is the free spectral range of the etalon, using this technique. The slight nonuniformity in the spacing of the observed modes is due to the shift of the cavity mode frequency due to variation of the cavity length during the 2 minute scan. Fine frequency control within the 500 MHz cavity mode spacing was achieved by PZT movement of a cavity of the tuning range has frequently been observed and the reason for it is not understood. Thus, it was verified that the laser output frequency could be continuously varied over a 2 GHz range. It should be mentioned that electrooptic or piezoelectric methods could also be used to vary the length of the intracavity etalon but temperature tuning is in the most convenient in the present experiments.

With frequency control of the laser output it is now possible to heterodyne two single-frequency Nd:YAG lasers at a variable frequency offset using the experimental configuration shown in Fig. 11. A second laser, identical to the one already operating, was constructed. Both lasers used 3 x 63 mm rods which were cut from the same boule of raw material and it is expected that the peak of the gain curve for the two lasers should be nearly at the same frequency. A Motorola MRD-500 PIN photodiode with a frequency response to approximately 2 GHz was used as the detector. Also available is a Philco L 4501 diode which has a response to 10 GHz. The photodiode output was displayed on an HP 8551B spectrum analyzer. On heterodyning the output from the two lasers a beat signal at approximately 1.6 GHz was immediately observed. The difference frequency was then varied from approximately 10 MHz (the minimum useful frequency of the spectrum analyzer) to 2 GHz by temperature tuning of one etalon and PZT mirror movement. A typical beat signal is shown in Fig. 12. The stability of the resultant signal was approximately $\pm$ MHz over a 10 second observation period and this is consistent with the Fabry-Perot display where each oscillator varies over a $\pm$ 60 MHz range during the same observation period. It was verified that the two lasers operate well within the etalon thermal tuning range.

Initial attempts to lock the two lasers together at a zero frequency offset were unsuccessful using a Lansing Model 80.210 lock-in stabilizer. This unit, which had been used to lock the laser output to a stable Fabry-Perot frequency reference, does not have adequate bandwidth. In the next attempt, one laser will be stabilized by locking it to the Fabry-Perot reference cavity and the second laser will then be locked to this stabilized laser.

REFERENCES

1. Hercher, M: Appl. Optics, 8, 1163 (1969).

2. Chester, R.: Applied Optics, 9, 2190 (1970).

3. Pound, R.: Rev. Sci. Inst., 17, 490 (1946).

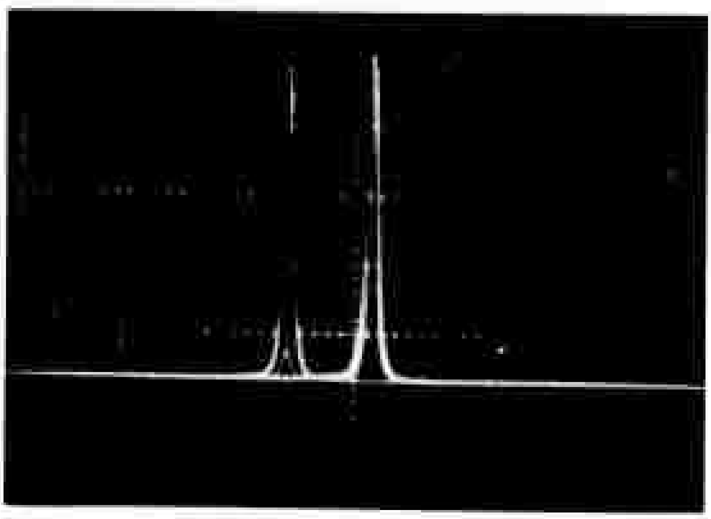
4. Ballik, E.: Phys. Letters, 4, 173 (1963).

5. White, A.: Rev. Sci. Instis., 38, 1079 (1967).

6. Hercher, M.: Appl. Optics, 7, 951 (1968).

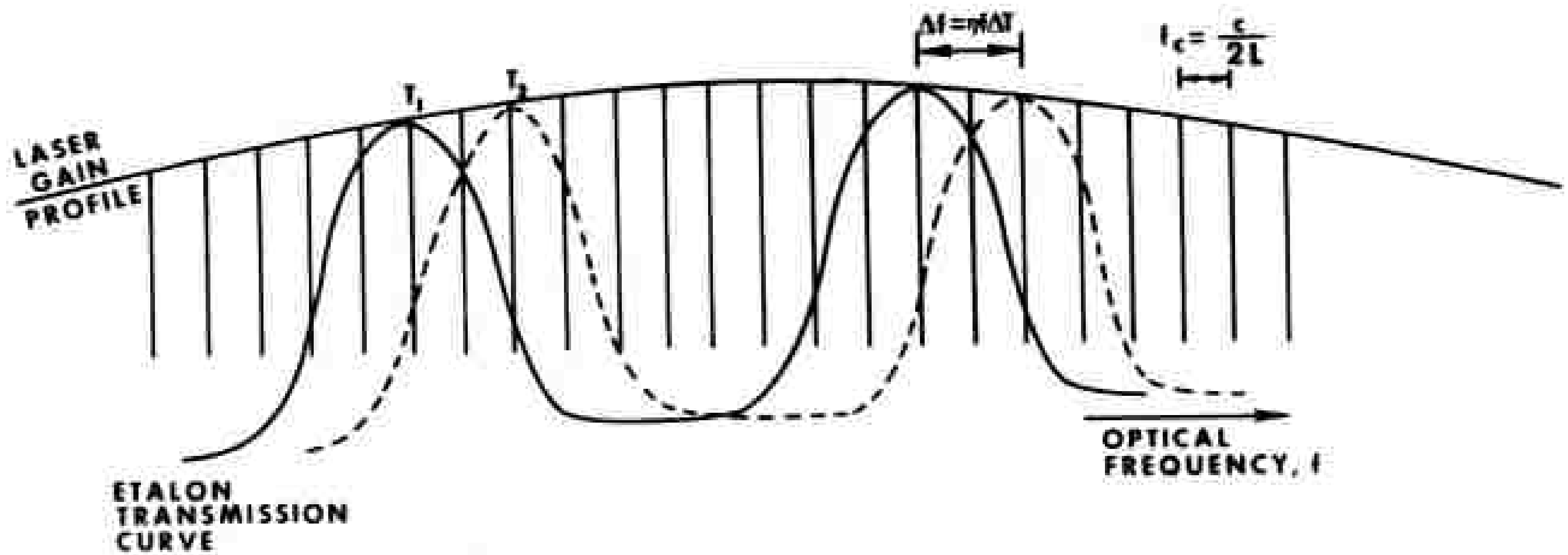
FIG. 1

INTRAMODE FREQUENCY INSTABILITY

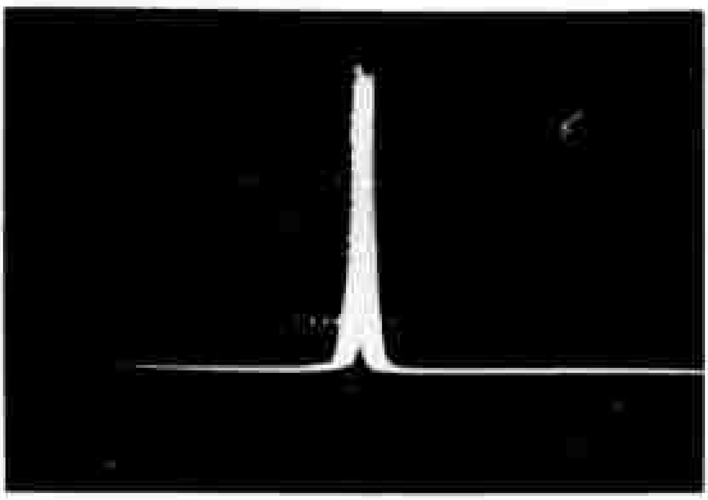


390 MHz/div

ETALON THERMAL TUNING CHARACTERISTIC

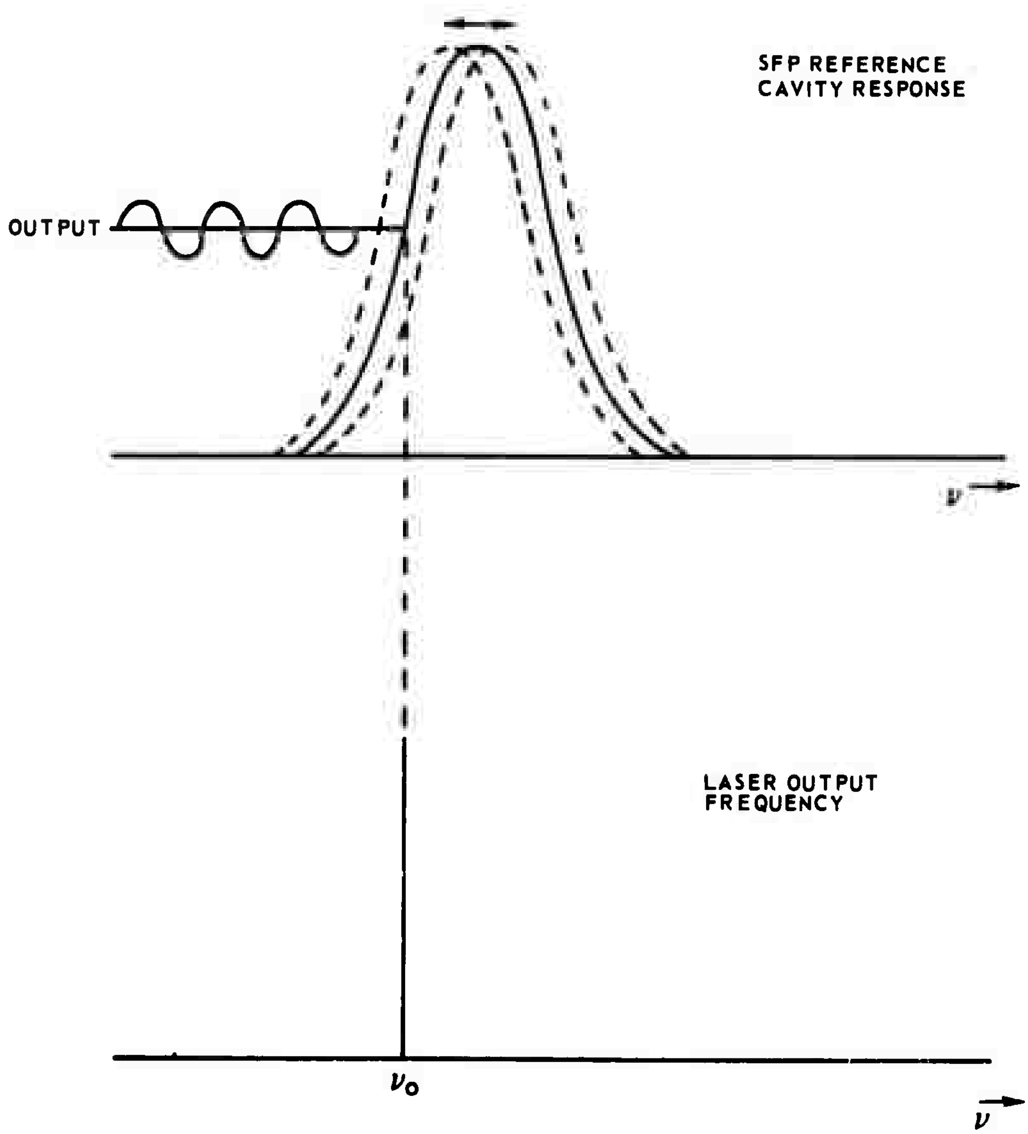


INTERMODE FREQUENCY INSTABILITY

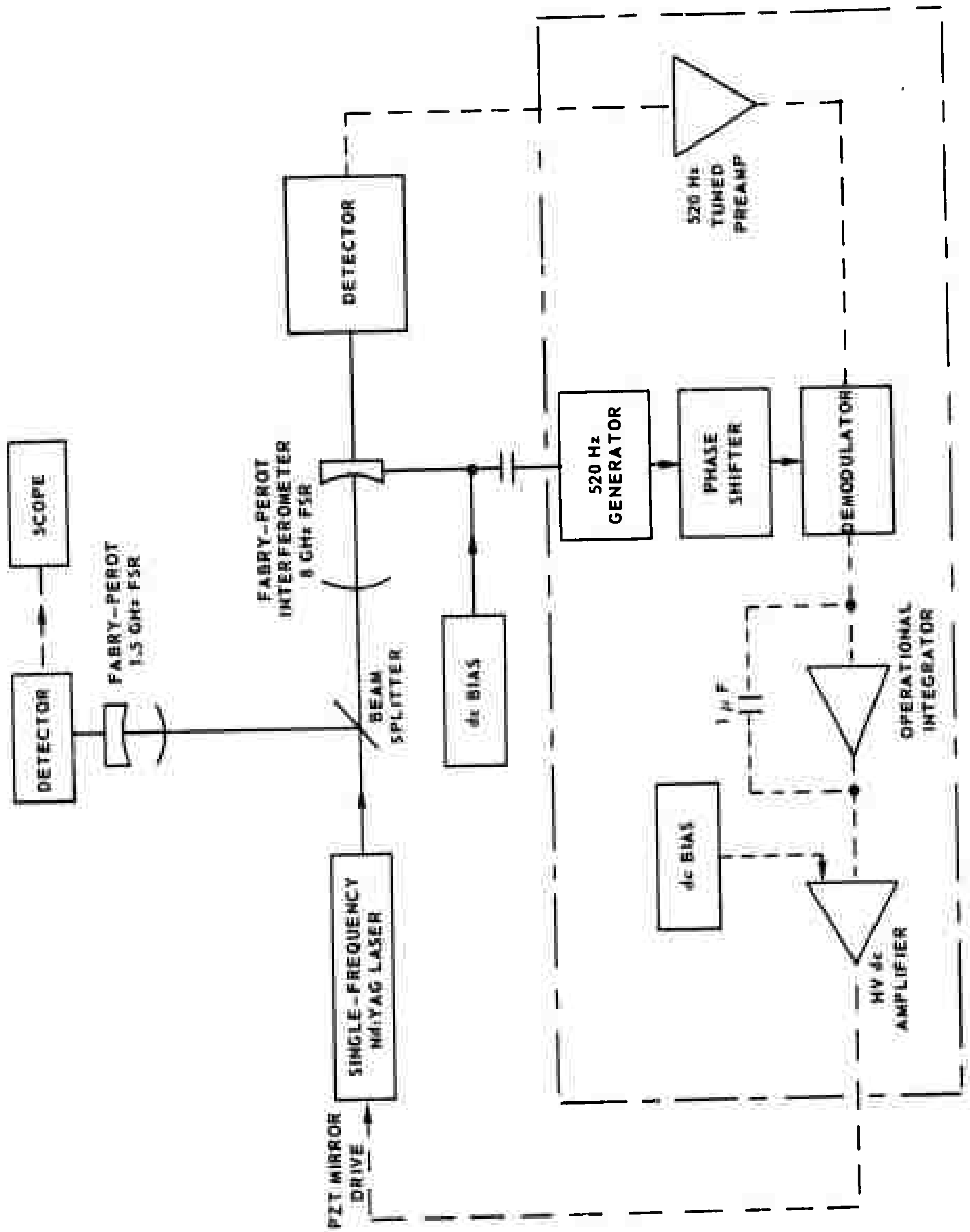


390 MHz/div

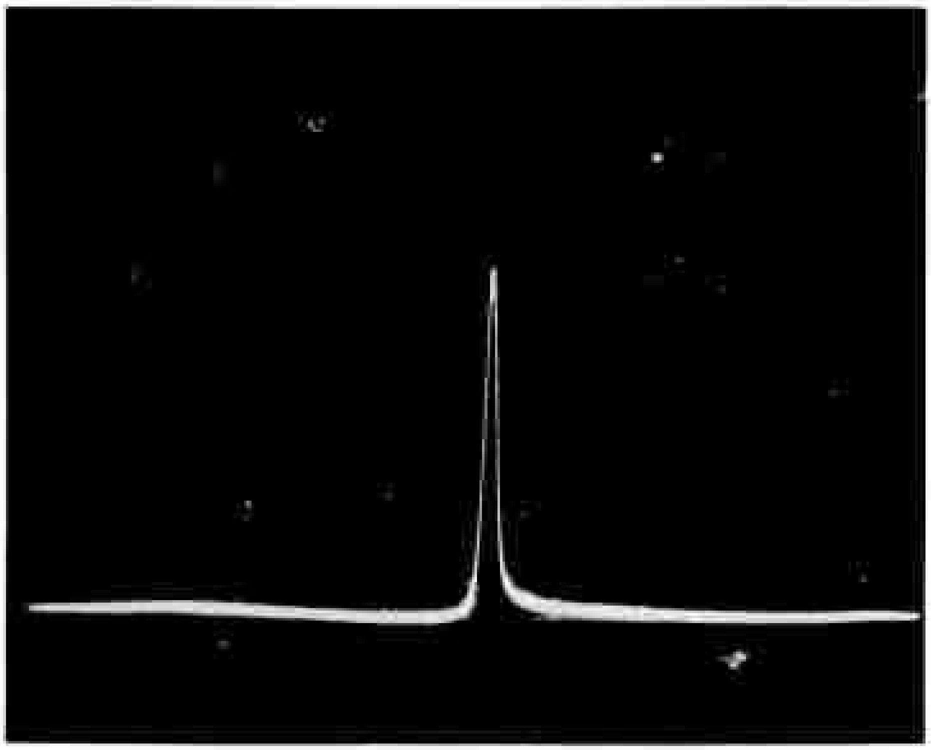
REFERENCE CAVITY RESPONSE



Nd:YAG FREQUENCY – STABILIZATION LOOP



SINGLE-FREQUENCY OUTPUT

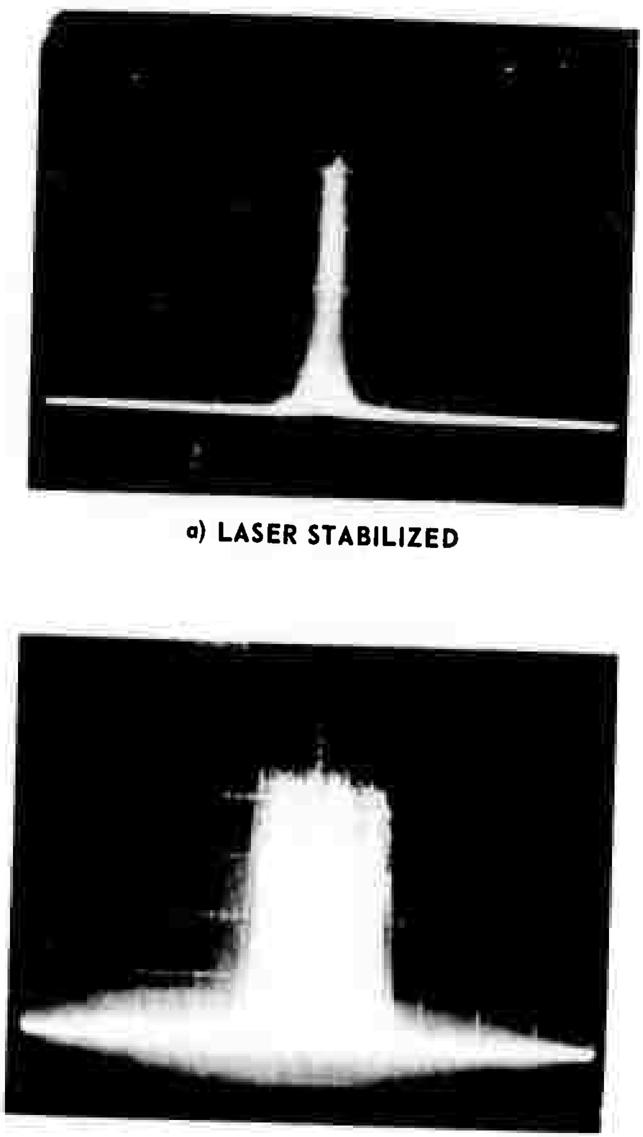


57 MHz/div

STABILIZED SINGLE-FREQUENCY Nd: YAG LASER

10 sec EXPOSURE

57 MHz/div

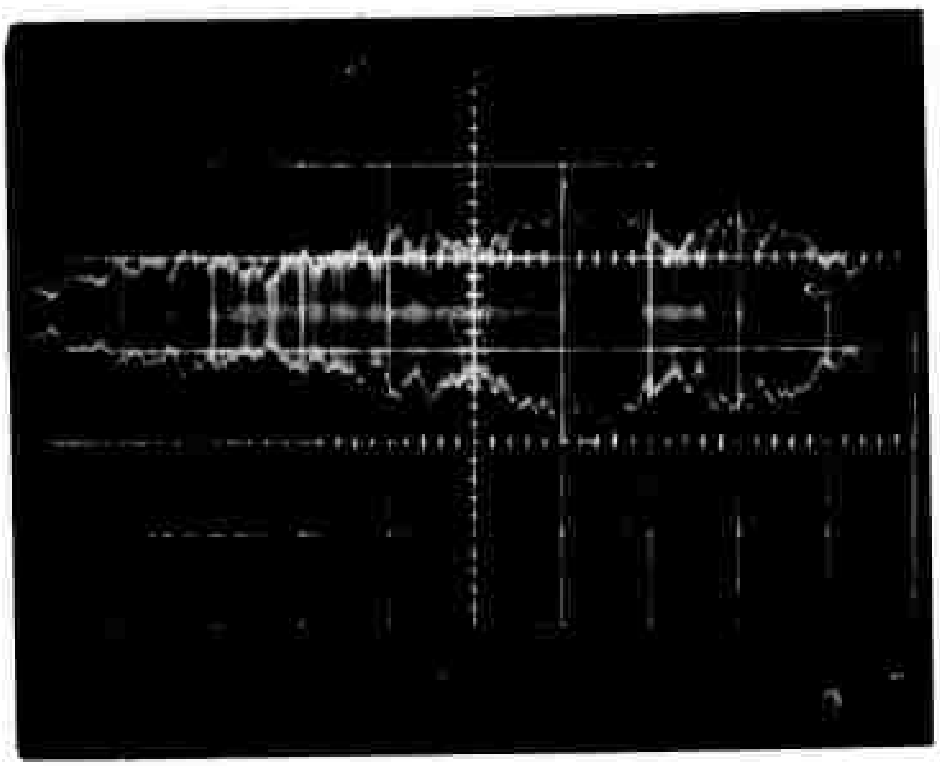


a) LASER STABILIZED

b) LASER FREE-RUNNING

520 Hz AMPLIFIER OUTPUT

LINEAR SCALE



0.2 sec/div

19.

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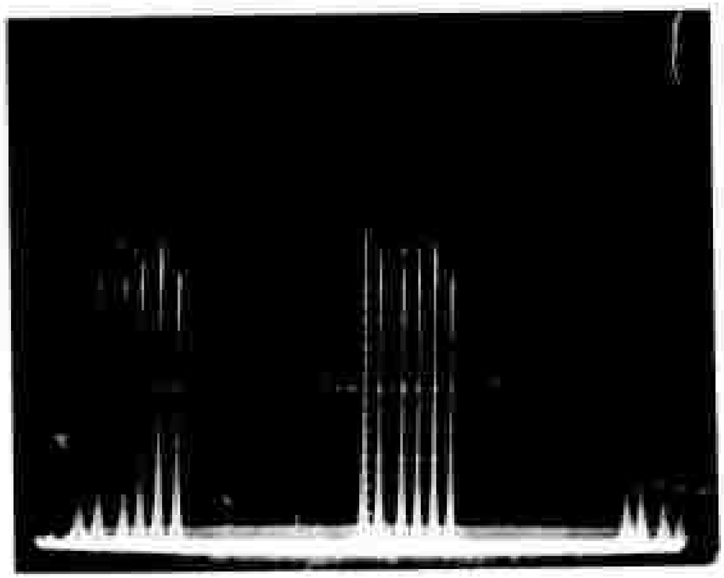
FIG. 9

TEMPERATURE TUNING OF Nd:YAG LASER



8GHz

DECREASING TEMPERATURE

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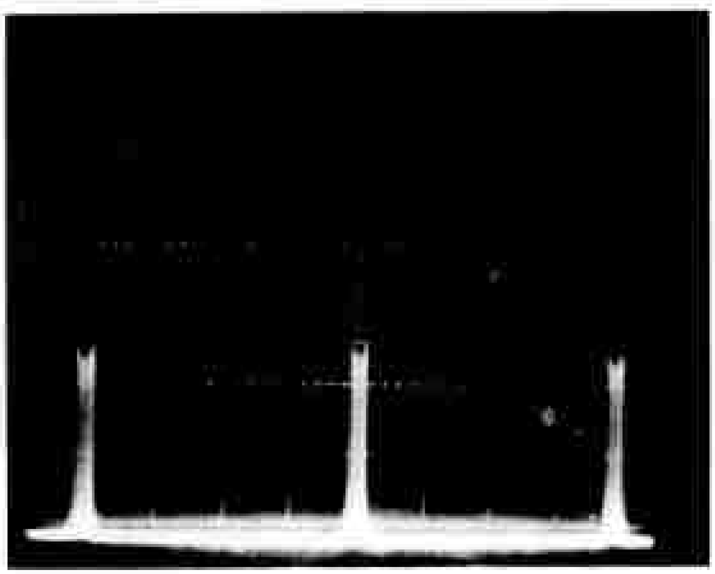
20.

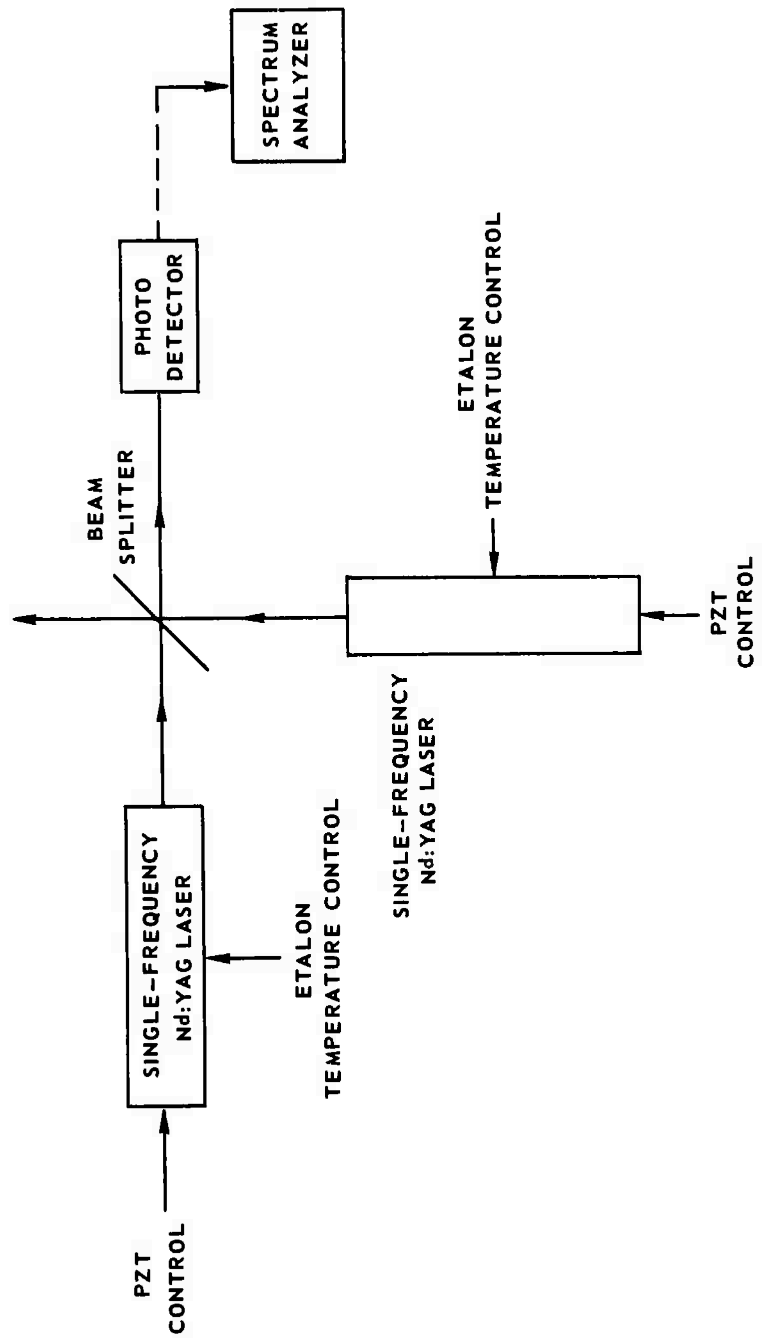
FIG. 10

PZT MIRROR-TUNING OF Nd:YAG LASER



|←— 8 GHz —→|

Nd:YAG SINGLE-FREQUENCY HETERODYNE EXPERIMENT



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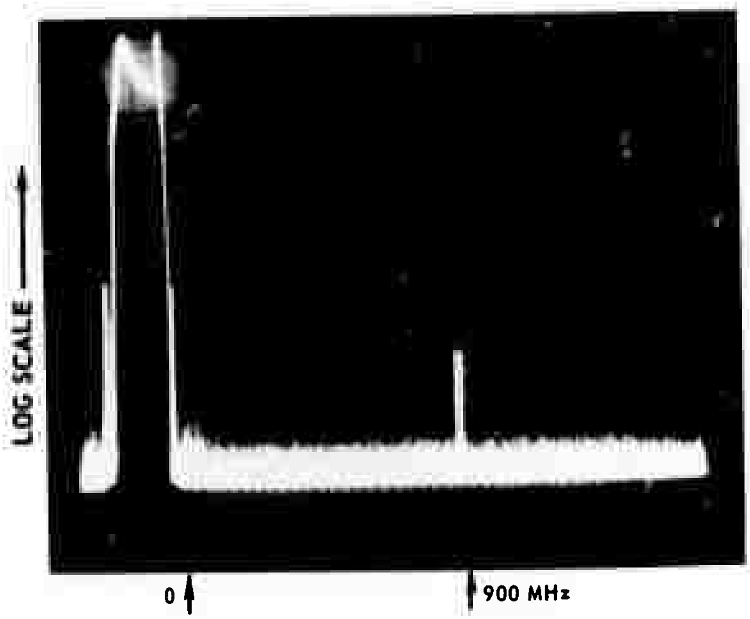
22. FIG. 12

HETERODYNED SIGNAL FROM TWO SINGLE-FREQUENCY Nd:YAG LASERS



FREQUENCY, 200 MHz/div